

Jeffrey Pine-Mixed Conifer Fire History and Forest Structure

With and Without Fire Suppression and Harvesting

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Key Findings

Fire History

- All three study areas experienced frequent fires before the onset of fire suppression. Return intervals for fires scarring 10% or more of sampled trees were: SSPM median 7-9 yrs (range 1 – 43), Sierraville median 6 yrs (range 1-67), and Bridgeport median 6 yrs (range 1-36).
- The intra-ring locations of fire scars for the Sierra Nevada sites were concentrated in the latewood and at the ring boundary suggesting mostly late summer and fall fires. Sierraville – earlywood 7.3%, latewood 2.4%, ring boundary 90.2%. Bridgeport – latewood 3.5%, ring boundary 89.5%.
- The intra-ring locations of fire scars for the SSPM sites were concentrated in the earlywood suggesting mostly spring and early-summer fires – earlywood 91%, latewood 8.5%, ring boundary 0.5%.
- The SSPM experienced a dramatic change in fire regime (fire frequency and proportion of trees scarred) in the early 1800s that did not occur in the eastern Sierra Nevada sites. In the SSPM, fires became less frequent with a higher proportion of trees scarred in each fire than previously.
- Superposed epoch analysis indicates years in which fires scarred multiple trees in each of the study areas were unusually dry years. Additionally, antecedent conditions played a significant role in the SSPM with unusually wet years preceding the fire years (up to 6 yrs in advance). However, only the dryness in the year of the fire was significant in the Sierra Nevada sites.
- Fire suppression began in the Sierra Nevada sites early in the 20th Century following the introduction of grazing in the late 1800s. The fire regime was dramatically altered at that time on both sites.
- Fire suppression began in the SSPM in 1970. Though it is limited in intensity in the SSPM, fire suppression since 1970 appears to be having a similar affect on the fire regime in the SSPM as did the early fire suppression of the 20th Century in the Sierra Nevada. The SSPM sites are currently experiencing an unusually long period without fire scars.

Stand Structure

- Stand structural characteristics in the SSPM varied spatially so much so that no measure of central tendency (average, median, mode) would adequately describe the distribution of tree density, stand basal area, DBH, or seedling density at the stand scale.
- Snag density in SSPM varied so greatly that no measure of central tendency (average, median, mode) would adequately describe the distribution of snag density. (26% of plots had no snags – 71% of plots had < the average).
- The distribution of tree sizes at the stand scale and the general lack of small trees and large, dead woody material on many sites, suggests that standard methods used in USA for describing seral stages do not adequately describe seral stages under more fully functioning fire regimes.

- Average density of trees > 2.5 cm dbh in the Sierra San Pedro Martir (SSPM) was 145.3 ha⁻¹ (58.8 ac⁻¹). Range of 30 – 320 ha⁻¹ (12 – 130 ac⁻¹).
- Average stand basal area in SSPM was 19.9 m² ha⁻¹ (86.7 ft² ac⁻¹). Range of 5.7 – 50.7 m² ha⁻¹ (24.8 – 220.8 ft² ac⁻¹).
- Average DBH of trees in SSPM was 32.6 cm (12.8 in). Range 2.5 – 112 cm (1 – 44 in).
- Average canopy cover in the SSPM was 25.3% (range 14 – 49.5%).
- Average seedling density in the SSPM was 124.7 ha⁻¹ (50.5 acre⁻¹). Range of 0 – 470 ha⁻¹ (0 – 190 acre⁻¹).
- Average sapling patch size in the SSPM was 0.01 ha (0.025 ac). Range 0.001 – 0.07 ha (0.0025 – 0.173 ac).
- Average snag density in the SSPM was 5.1 ha⁻¹ (2 acre⁻¹). Range of 0 to 10 ha⁻¹ (0 – 4.1 acre⁻¹).

Key Implications for Management

- Understanding and quantifying the spatial variability in stand structure and landscape patterns that are generated by unaltered fire regimes is key to developing appropriate management and restoration goals and guidelines.
- Standards and guidelines that specify stand-level average conditions as targets for such features as snags, dead woody material, canopy cover, tree density, tree spacing, etc. are not likely to restore or achieve the spatial diversity of structure and habitat conditions generated by more fully functioning fire regimes.
- Seral stages in forests with more fully functioning fire regimes of frequent, low-moderate intensity surface fires are likely to be quite different than seral stage descriptions developed from forests in which fire regimes have been altered for many decades as in much of the Sierra Nevada.

1. INTRODUCTION

High intensity wildfires have become more common in yellow pine forests (Jeffrey or ponderosa pine) of the western United States over the last several decades. Many have suggested this is largely due to changes in stand structures and composition from past logging and systematic fire suppression of the last century (Agee, 1993; Arno & Allison-Bunnell, 2002). There is currently debate on appropriate target conditions for fire hazard reduction and forest restoration (Millar & Woolfenden, 1999; Swetnam et al., 1999). This is due to the lack of forests functioning under an unaltered fire regime that could serve as restoration references in the western US (Allen et al., 2002; Taylor 2004).

Fire regimes of Jeffrey pine forests are usually similar to, though more variable than, ponderosa pine forests – frequent, low-moderate-intensity surface fires (Skinner and Chang 1996). The greater variability of fire frequency is likely due to the harsher conditions, both edaphically and climatically, Jeffrey pine forests grow in when compared to ponderosa pine (Jenkinson 1990). These differences likely influence spatial and temporal patterns of fuel accumulation influencing the local fire regime (Skinner and Chang 1996; Taylor and Skinner 2003).

The Jeffrey pine-dominated, mixed-conifer forests of the Sierra San Pedro Martir (SSPM), Mexico, have not experienced logging and have only recently (1970) begun to experience limited fire suppression (Minnich et al., 2000; Stephens et al., 2003). Thus, the SSPM is unique within the California floristic province in that fires have regularly influenced its forests for most of the 20th Century similar to those that once occurred in yellow pine forests throughout the western United States. The mixed conifer forests of the SSPM may provide information on reference conditions for yellow pine forests of the western USA that were originally characterized by frequent, low to moderate intensity fires. This information could be used to help develop target stand conditions for reducing the fire hazard and improving forest resilience in large portions of California and Nevada Jeffrey pine dominated mixed conifer forests.

2. SUMMARY OF PROJECT OBJECTIVES

The objectives of this project were to compare fire history and stand structures in Jeffrey pine-dominated forests of the Sierra San Pedro Martir (SSPM), Baja California Mexico, and the eastern Sierra Nevada, California. The forests in the SSPM have not been harvested and have experienced only limited fire suppression beginning in the 1970's. The sampled forests in the eastern Sierra Nevada have not been harvested but fire exclusion has occurred for approximately 100 years. Information from this study may be useful in the development of desired conditions and developing restoration goals in similar forests of the western US.

3. SUMMARY OF MATERIALS AND METHODS

The study was be conducted in three areas: the SSPM which are approximately 100 km SE of Ensenada, Mexico, the Sierraville Ranger District of the Tahoe National

Forest (Lemmon Canyon), and the Bridgeport Ranger District of the Humboldt-Toiyabe National Forest (Lost Canon), California. The conifer species common to all three mixed conifer forests are Jeffrey pine (PIJE), white fir (ABCO), sugar pine (PILA), incense-cedar (CADE), and lodgepole pine (PICO). Our JFS proposal specified that we would work on one site in the SSPM and one in the eastern Sierra Nevada. However, since the eastern Sierra sites were small, we expanded the study to two sites.

Measurement of forest composition and structure was done in the SSPM using a systematic design of nested plots; the starting point of the grid was selected randomly. Each plot was separated by 200 m and a total of 49 plots were sampled (7 x 7 grid). Live trees were inventoried using 0.1 ha circular plots. On each of these plots, all trees greater than 2.5 cm at DBH were measured for DBH and species. All seedlings (DBH less than 2.5 cm) inside the 0.1 ha plot were counted by species. The 7 x 7 grid of plots was installed only in the SSPM.

After extensive consultations with USFS personnel in the eastern Sierra Nevada (Tahoe, Bridgeport, and Plumas National Forests), we were able to find only four areas of approximately 4 ha in size of Jeffrey pine dominated forests that had not been harvested and had granitic parent material similar to the SSPM. Of these sites, we selected Lemmon Canyon on the Sierraville Ranger District and Lost Cannon on the Bridgeport Ranger District.

In the SSPM, a 0.25 ha plot was established to measure snags using the same center point as the live tree plot. The plot for measuring snags is larger than the live tree plot because the density of snags is much lower than that of live trees. On the 0.25 ha plots, all snags over 5 cm DBH were measured for DBH. Snag species was determined from the bark or wood characteristics. Snags decayed such that species could not be determined were recorded as an unknown species. In addition to species and DBH, decay class (e.g., Cline et al. 1980) was recorded for each snag.

Surface and ground fuels were sampled at each plot (7 x 7 grid) using the line intercept method (Brown 1974). Using the plot center, three transects with random directions were installed. One and ten hour fuels were sampled from 0-3 meters, 100 hour fuels from 0-5 meters, and 1000 hour and larger fuels from 0-13 meters on each transect. Duff and litter fuel depth was measured at 3 and 5 meters on each transect. Ground and surface fuel loads were calculated by using appropriate equations developed to predict fuel loads in mixed conifer forests (van Wagtenonk et al. 1996).

Approximately 20-40 fire-scarred samples from were obtained from trees, stumps, and down logs on all three sites to determine fire history. Fire-scar specimens were removed with a chainsaw. Live trees were sampled more conservatively by extracting a small wedge of living tissue from the scarred area. All fire scar samples were taken to the laboratory and sanded to 400 grit. Calendar years were assigned to each fire scar using crossdating techniques and composite fire histories were produced for each site. The season of past fire occurrence was estimated from the position of the scar in the annual ring. Fire-climate interactions were investigated using superposed epoch analysis (Swetnam & Betancourt 1998). The FHX2 software package was used to analyze fire history information (Grissino-Mayer 2001).

At each of the three sites, a 4 ha plot was randomly located to determine spatial regeneration patterns and if regeneration is correlated with past fires or climate. In this plot the X and Y coordinates of all trees and seedlings was measured and all trees above

5 cm DBH were bored to determine tree age. All increment cores were crossdated to determine tree age. Spatial statistics were used to determine tree and regeneration patterns (clumped, uniform, random). A 4 ha plot was used because it was likely to include 1000-2000 trees and the size of the plot was likely to incorporate most of the spatial heterogeneity of these forest types.

The software package SPPA 2.0.3 was used to analyze the spatial pattern of trees on the sampled sites (Haase 1995). In a first step, the univariate spatial tree distribution was evaluated for each group using Ripley's K function (Ripley 1981, Diggle 1983). To assess whether regeneration occurs in gaps or evenly distributed over the site, the spatial association between the smallest tree class and the larger trees was investigated with a modified procedure for analysis of bivariate distribution patterns within SPPA software (Haase et al. 1996). All Ripley's-K analysis was calculated at the 95%-confidence level. In the present study the K-function was computed from 1 m intervals up to a maximum of 15 m, thereby looking at relatively fine-scale spatial pattern consistent with the expected fine-scale affects of low to moderate severity fires.

The shape, abundance, size, and structural characteristics of sapling regeneration patches in the SSPM was investigated. This analysis was not possible in the California sites because they were too small (4 ha). The regeneration patch regime in the SSPM was quantified by sampling patches on seven 1200 m, permanently marked line transects. For all patches intersected, tree size, species, age, and patch canopy cover were recorded. Patch structural characteristics were statistically compared to data from unbiased forest inventory plots. The smallest regeneration patch was three saplings (DBH 2.5 – 15 cm) in a 49 m² area. Patch fraction and abundance were quantified.

In each patch the longest axis (A major) and the maximum axis perpendicular to the longest axis (A minor) was measured (m). The end of the axis was located on the outside canopy drip line of patch perimeter trees. Patch characteristics (i.e. area and perimeter) were estimated as a function of the major and minor axes. Since the patches were irregular in shape, we compared equations for area and perimeter for patches assuming they were shaped as an ellipse, a rhombus, and equations developed from linear regressions. These equations were generated from a subsample of patches (detailed patches that included one-third of the total number of patches). Detailed patches were measured by recording the distance (m) of multiple radii (every 45 degrees) from patch center to patch edge (outside canopy drip line of perimeter trees) and then summing the areas of the resulting triangles.

4. RESULTS

4.1 SSPM Stand Structure

4.1.1 SSPM Snags

The majority of the snags inventoried were Jeffrey pine (52.6%), with fewer from white fir (23.1%), sugar pine (5.1%), and lodgepole pine (1.3%); 17.9% of snags could not be identified to species (Stephens 2004). Average snag DBH was 57.9 cm (standard error = 3.0) for all species (Table 1). Snag DBH varied from 2.6 to 111.3 cm. The majority of the snags were relatively large (Stephens 2004).

Table 1. Cumulative percentage of snags by size class and species from Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico. DBH – diameter at breast height.

Snag size class (cm)	PIJE	ABCO	PILA	PICO	UNK	Total
DBH > 10	100	88.89	75.00	100	100	93.75
DBH > 20	100	77.78	75.00	100	100	91.25
DBH > 30	87.80	61.11	75.00	100	100	83.75
DBH > 50	73.17	50.00	50.00	0	64.28	62.50
DBH > 75	31.70	27.78	50.00	0	35.71	31.25
DBH > 100	4.87	16.67	0	0	7.14	7.50

Jeffrey pine snags were equally distributed in the three condition classes (Table 2). There were fewer condition class 1 white fir snags, over two-thirds of the white fir snags were in condition class two (Table 2). Condition class 3 dominated snags that could not be identified to species. Nineteen more snags were added in 2002 and 2003 (during the major drought) (15 Jeffrey pine, 3 white fir, 1 lodgepole pine) and this changed the condition class distribution of Jeffrey pine snags to 50% class 1, 27% class 2, and 23% class 3.

Table 2. Percentage of snags by condition class from Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico in 2000.

Snag condition	PIJE	ABCO	PILA	PICO	UNK
Some needles and small branches attached, rating 1	31.7	23.5	25.0	100	0
No needles, most small branches absent, stubs formed as the tips of large limbs broke, rating 2	36.6	64.7	25.0	0	21.4
Most branches broken off, only stubs of the largest limbs remain, rating 3	31.7	11.7	50.0	0	78.6

Average snag density in 2003 was 5.10 snags/ha, (range 0-25 snags/ha, standard error 0.80), with 26% of the plots having no snags (Figure 1). Less than average density was recorded on 71% of plots. Ten percent of the plots had a snag density greater than 10 snags/ha. Average snag basal area was 1.67 m²/ha (range 0 – 6.45 m²/ha, standard error 0.25). Average snag DBH was 58.1 cm (standard error = 2.7) for all species. Snag DBH varied from 2.6 to 111.3 cm.

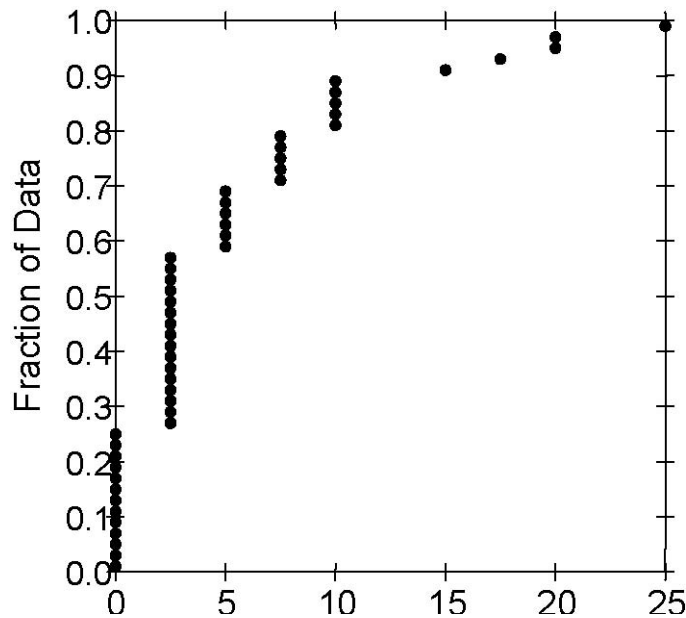


Figure 1. Snag density (ha^{-1}) distribution from Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico, in 2003.

4.1.2 SSPM Fuels

Surface and ground fuels were measured using 147 planar transects. Average total surface fuel loads were 15.8 tons/ha (range 0.01 – 159.74 tons/ha, standard error 3.91) (Table 3). Average ground fuel loads were 8.7 tons/ha (range 0.43 – 23.91 tons/ha, standard error 0.83) (Table 3). Ground fuels consisted of only litter (average depth of 1.6 cm, range 0 – 10.0 cm), no duff was recorded.

Total surface fuel load was less than the average load in 73% of plots. Surface fuel load was greater than 18.4 tons/ha on 24% of plots, and greater than 36.8 tons/ha on 8% of plots. Average 1000-hr fuel load was 13.64 tons/ha (Table 3). Thirty-seven percent of plots had no 1000-hr fuels, 67% had less than the average load, and 22.4% of plots had greater than 20 tons/ha. Fifty-six percent of 1000-hr fuels are found on 10% of the plots, 75% are located on 20% of the plots. Eighty-one percent of the 1000 hour fuel load was from rotten materials, the remaining 19% was from sound wood.

Table 3. Surface and ground fuel loads from Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico.

Fuel class	1 hr	10 hr	100 hr	1000 hr	Total Woody and down	Litter
Average (ton/ha)	0.11	0.85	1.20	13.64	15.80	8.69
Maximum (ton/ha)	0.89	6.98	8.80	156.41	159.74	23.91
Minimum (ton/ha)	0	0	0	0	0	0.43
Standard error	0.03	0.16	0.27	3.84	3.91	0.83

4.1.3 SSPM Stand Variation

Histograms of live-tree diameters for the sampled plots have a great deal of variation (Figure 2). However, an inverse-J diameter distribution is produced when all plots are combined (Figure 3) (Stephens & Gill 2005).

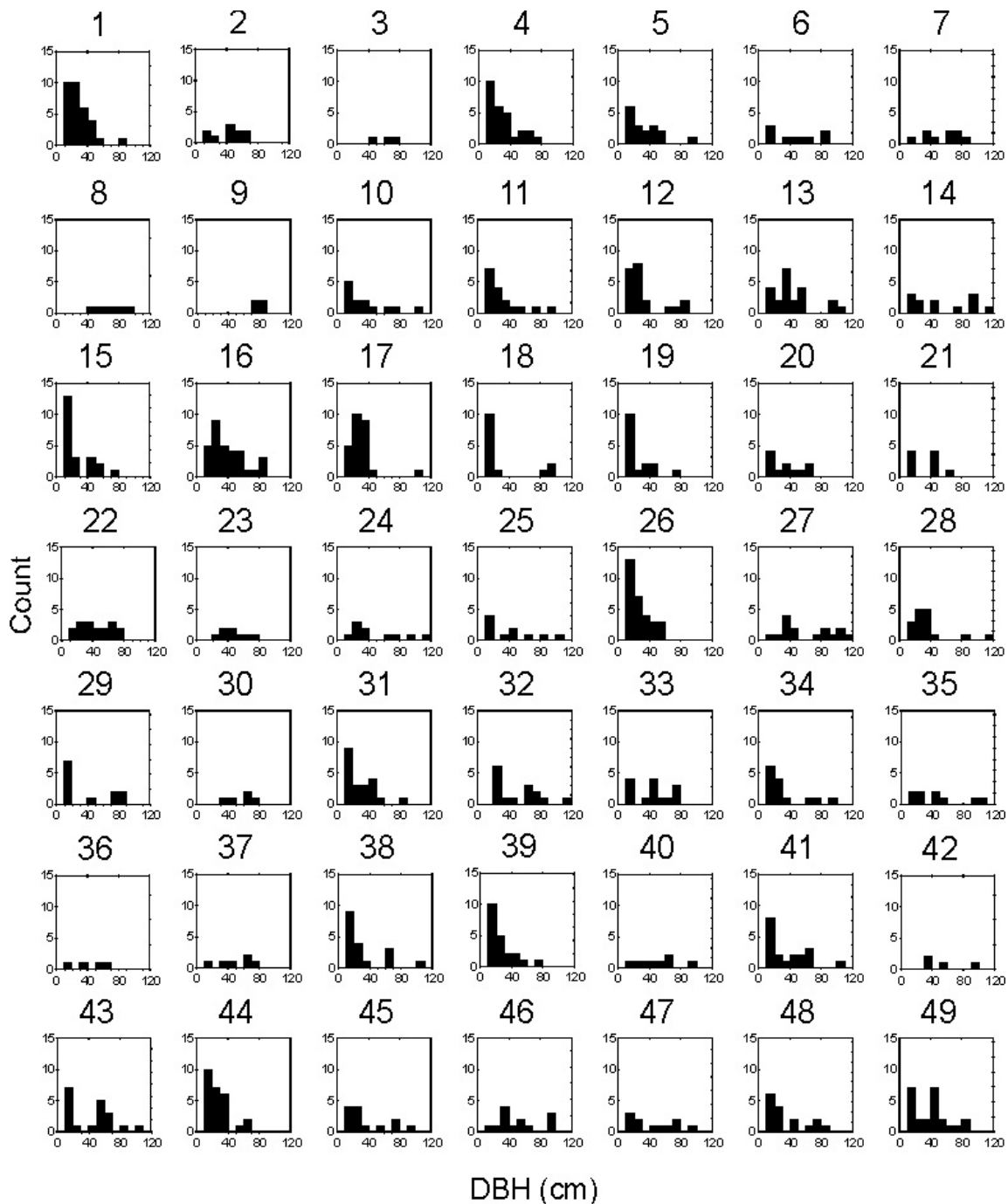


Figure 2. DBH histograms for the 49 plots in Jeffrey pine-mixed conifer forests of the Sierra San Pedro Martir, Mexico. X and Y scales are similar (x max = 120, y max = 15). Plot number is shown on top of each column.

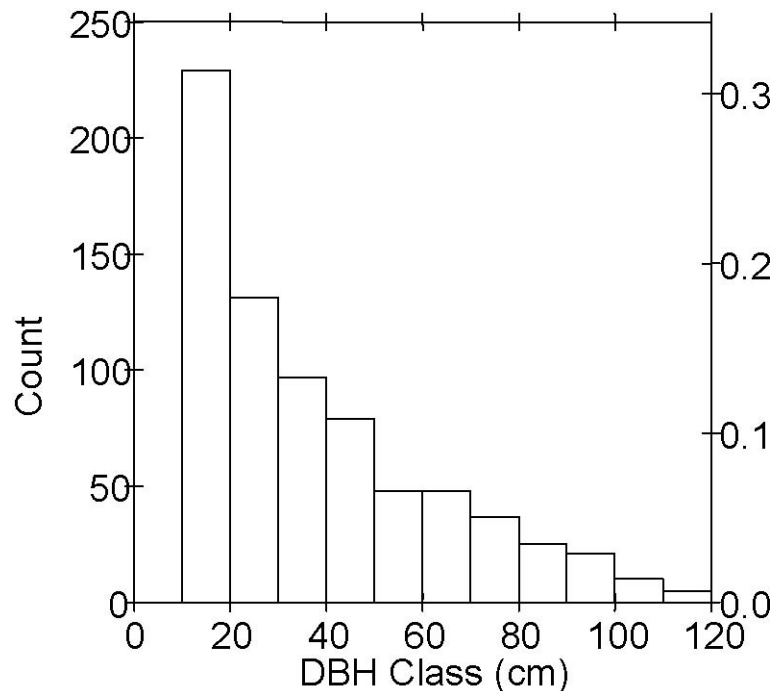


Figure 3. Histogram of DBH classes for the 49 inventory plots in Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico.

Average DBH of all trees was 32.6 cm (S.E. 0.9, range 2.5-112 cm) (Table 4). Sugar pine had the largest average DBH. Ninety-three trees (12.7%) had a DBH > 65 cm, more than twice the mean DBH. Average tree density was 145.3 trees ha⁻¹ (S.E. 10.4, range 30 - 320 trees ha⁻¹). Jeffrey pine is the most common tree in the sampled area (76% of plot stocking). Approximately 13% of plots have tree densities from 220 - 320 trees ha⁻¹. Three plots (6.1%) had a tree density > 290, more than twice the mean density. One plot in a riparian area contained a small number of quacking aspen.

Average basal area was 19.9 m² ha⁻¹ (range 5.7-50.7 m² ha⁻¹). Plot basal area was dominated by Jeffrey pine (67.1 %), white fir (23.1%), and a smaller amount of sugar pine and lodgepole pine (Table 4). Approximately 20% of the plots had a basal area below 14 m² ha⁻¹, 60% of plots had basal areas from 14-22 m² ha⁻¹, and 20% of plots had basal areas of 22-50 m² ha⁻¹. Only 2 plots (4.1%) had a basal area > 40 m² ha⁻¹, more than twice the mean basal area.

Average seedling density was 124.7 ha⁻¹ (S.E. 15.7, range 0-470 seedlings ha⁻¹). Eighty-one percent of seedlings were Jeffrey pine followed by white fir (11%), sugar pine (7.7%), and lodgepole pine (0.3%) (Table 4). Six percent of plots had no seedlings, 30% had a density below 50 ha⁻¹, 50% of plots had a density from 50 – 200 ha⁻¹, and 20% of plots had a seedling density of 200 – 470 ha⁻¹. Five plots (10.2%) had a seedling density > 250, more than twice the mean seedling density.

Table 4. Tree and seedling characteristics from 49 plots in Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico. S.E. - standard error of the mean.

Total number of trees	PIJE 541	ABCO 129	PILA 43	PICO 17	Total 730
DBH (cm)					
Average (S.E)	30.8 (1.0)	38.6 (2.6)	40.4 (4.6)	26.4 (4.5)	32.6 (0.9)
Median	23.8	34.7	32.5	21.5	25.7
Min/max	2.5/112	3.4/110.1	3.8/109	4.7/69.6	2.5/112
Basal area (m² ha⁻¹)					
Average	13.35	4.60	1.67	0.28	19.9
Percentage	67.1	23.1	8.4	1.4	100
Min/max	5.7/9.85	0/8.59	0/6.36	0/8.57	5.7/50.7
Tree density (ha⁻¹)					
Average (S.E)	110.4 (10.3)	26.3 (5.2)	8.8 (2.7)	3.5 (2.0)	145.3 (10.4)
Median	80	10	0	0	140
Min/max	0/290	0/160	0/110	0/90	30/320
Seedling density (ha⁻¹)					
Average (S.E.)	101.2 (13.5)	13.5 (2.9)	9.6 (3.3)	0.4 (0.3)	124.7 (15.7)
Median	60	0	0	0	100
Min./Max.	0/410	0/80	0/140	0/10	0/470

Hierarchical cluster analysis identified 5 groups of plots with similar characteristics (Table 5). Group 1 includes a small number of plots with a few large trees. Group 2 includes plots with a small number of large trees but with a larger DBH range than in group 1. Group 3 includes plots with bimodal diameter distributions. Group 4 includes plots with an inverse-J distribution with high diameter averages. Group 5 also includes plots with an inverse-J distribution but with a lower average diameter and a smaller diameter range when compared to group 4 (Table 5). De Liocourt's constant (q-factor) for group 4 and 5 was 3.08 and 1.56, respectively. De Liocourt's constant for all 49 plots was 1.50. There are no discernable geographic arrangement of the classified forest groups (semi-variogram of tree density, basal area, or average DBH indicated no spatial autocorrelation).

Table 5. Summary statistics for DBH classes by groups identified in cluster analysis and for all 49 plots combined in Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico.

	<i>Group 1</i>	<i>Group 2</i>	<i>Group 3</i>	<i>Group 4</i>	<i>Group 5</i>	<i>Total</i>
Number of plots	4	12	12	10	11	49
Plot numbers	3, 8, 9, 30	2, 6, 7, 16, 20, 23, 33, 36, 37, 49	13, 14, 24, 25, 27, 32, 35, 40, 42, 43, 46, 47	5, 10, 11, 17, 18, 28, 34, 38, 41, 45	1, 4, 12, 15, 19, 26, 29, 31, 39, 44, 48	
Number of trees	18	153	148	167	244	730
Minimum DBH	30	10	10	10	10	10
Maximum DBH	90	80	110	110	80	110
Mean DBH	62.22	37.39	44.66	28.92	24.63	33.27
S.E.	3.92	1.73	2.43	1.90	1.19	0.92
Median DBH	65	40	40	20	20	30
Skewness	-0.40	0.30	0.62	1.57	1.43	1.04
Kurtosis	-0.62	-0.96	-0.77	1.66	1.31	0.23

Average overstory canopy cover was 25.3% (S.E. 3.81, range 14 – 49.5%). The transect with a canopy cover of 49.5% passed through a seasonal creek (Lucky Creek). Jeffrey pine was the species that dominated canopy cover (average of 19.2%) followed by white fir (average of 5.6%).

4.2. Fire History

4.2.1. Sierra San Pedro Martir

The majority of fire-scar specimens were taken from live Jeffrey pine trees (76 percent), with fewer taken from sugar pine, white fir, snags, and down logs (Stephens et al. 2003). Since the SSPM has not experienced forest harvesting, no stumps were available. Missing rings occurred on most specimens and specific years were predictable

as a subset of those indicated as very narrow rings by the San Pedro Martir chronology (Stokes et al. 1971).

One hundred and five fire years were identified from 1034 cross-dated fire scars in 105 specimens from two SSPM fire history plots. Fires were recorded between 1521 and 1980. Sixty-seven fires scarred 53 specimens between 1527 and 1980 on plot S1 and 86 fires scarred 52 specimens on plot S2 between 1521 and 1962. Plots S1 and S2 were separated by approximately 5 km and each is approximately 50 ha in size. A larger plot area was used to determine the number of spot fires in a moderately sized area. Twenty-six (39%) fires in site S1 and 38 (44%) fires in site S2 were detected on only single trees. Fires occurred synchronously on both sites in 12 years.

Fires were found to have been frequent during the period of record (Figure 4). Though fire scars were dated back to 1521, the number of fire scarred specimens drops off rapidly before 1700 at S1 and 1650 at S2. We selected 1700 as the cutoff date for composites based on visual inspection of Figure 1 and output from program SSIZ. Mean and median fire return intervals varied depending on the composite scale selected and number of trees required to be scarred before the fire is recorded in the composite fire summary. However, median fire return intervals were shorter than 15 years (majority less than 10 years) for all composite scales and years between fires varied from 1-43 years on individual trees (Table 6). The current fire-free interval is unusually long ($p < .001$) and may have been influenced by the fire suppression activities that began in the 1970s. Median fire return intervals in the forests of the SSPM are similar to forests dominated by similar species in California (Skinner and Chang 1996; Stephens 2001).

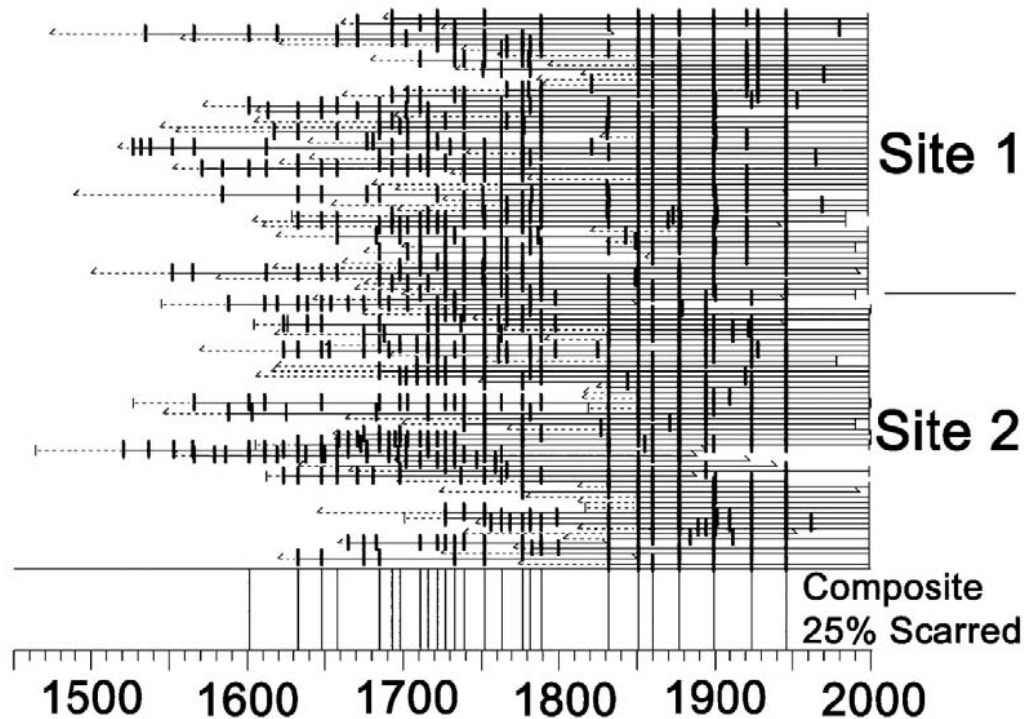


Figure 4. Historical fire activity of site 1 (Jeffrey pine mixed conifer forest) and site 2 (Jeffrey pine forest) in the Sierra San Pedro Martir, Baja California, Mexico.

Table 6. Fire return interval data - entire period of record for each site - C01=composite of all fire scars; C02=composite of fires scarring 2 or more trees; C10=composite of fires scarring 2 or more and at least 10% of available recording trees (ART); C25=composite of fires scarring 3 or more trees and at least 25% of ART.

Composite Scale	N Intervals	Median	Mean	Min	Max	Current	p^a	Last Fire
Site 1								
C01	66	5	6.9	1	32	18	<.10	1980
C02	40	8	9.9	1	32	52	<.001	1946
C10	35	9	11.3	1	43	52	<.001	1946
C25	27	13	14.5	5	43	52	<.001	1946
Site 2								
C01	70	5	5.7	1	25	37	<.001	1962
C02	34	7	9.5	1	43	53	<.001	1946
C10	31	7	10.4	2	43	53	<.001	1946
C25	24	10.5	13.0	4	43	53	<.001	1946

Note: ^a p =probability of an interval as long as the current interval based upon the Weibull distribution of past FRIs for each scale.

A discontinuity in the fire scar record is apparent during the early 19th century at each site (Figure 4). FRIs appear to be generally shorter before the discontinuity than afterwards. To test for differences between the two periods and between each century at each level of compositing, we determined the median, mean, minimum, and maximum FRI for each site for the different periods. The Student's t-test was then used to determine if significant differences ($p < 0.05$) existed in the mean fire interval (MFI). The differences in MFI's were statistically significant for composite scales C02, C10, and C25 at S1 and C10 at S2.

Intra-annual ring position of the scars was determined for 416 (82%) scars on S1 and 369 (72%) scars on S2. It is notable that only 4 scars (0.5 %) from the study occurred at the ring boundary that would be associated with dormant season fires. Of the scars in which season could be determined, 91% were located in the earlywood (EE, ME, LE positions) of the annual growth rings (Table 7).

Table 7. Position of fire scars within annual growth rings from fire scar specimens for each SSPM site. Site 1 Jeffrey pine mixed conifer, site 2 Jeffrey pine.

Season	<i>Site 1</i>		<i>Site 2</i>	
	n	% w/season	n	% w/season
D	4	1.0	0	0
EE	175	42.1	193	52.3
ME	131	31.5	108	29.3
LE	67	16.1	40	10.8
LW	39	9.4	28	7.6
UNK	107		142	
Total	523		511	

Fires that scarred more than 10% of trees in the study sites occurred during years of low precipitation (PDSI43 $p < .01$, SWD $p < .01$) and the two years preceding the fire year were wet (PDSI43: year -1 $p < .01$, year -2 $p < .05$) (Figure 5). Years in which fires scarred <10% of sampled trees or in which no fire was detected showed no association with the precipitation indices.

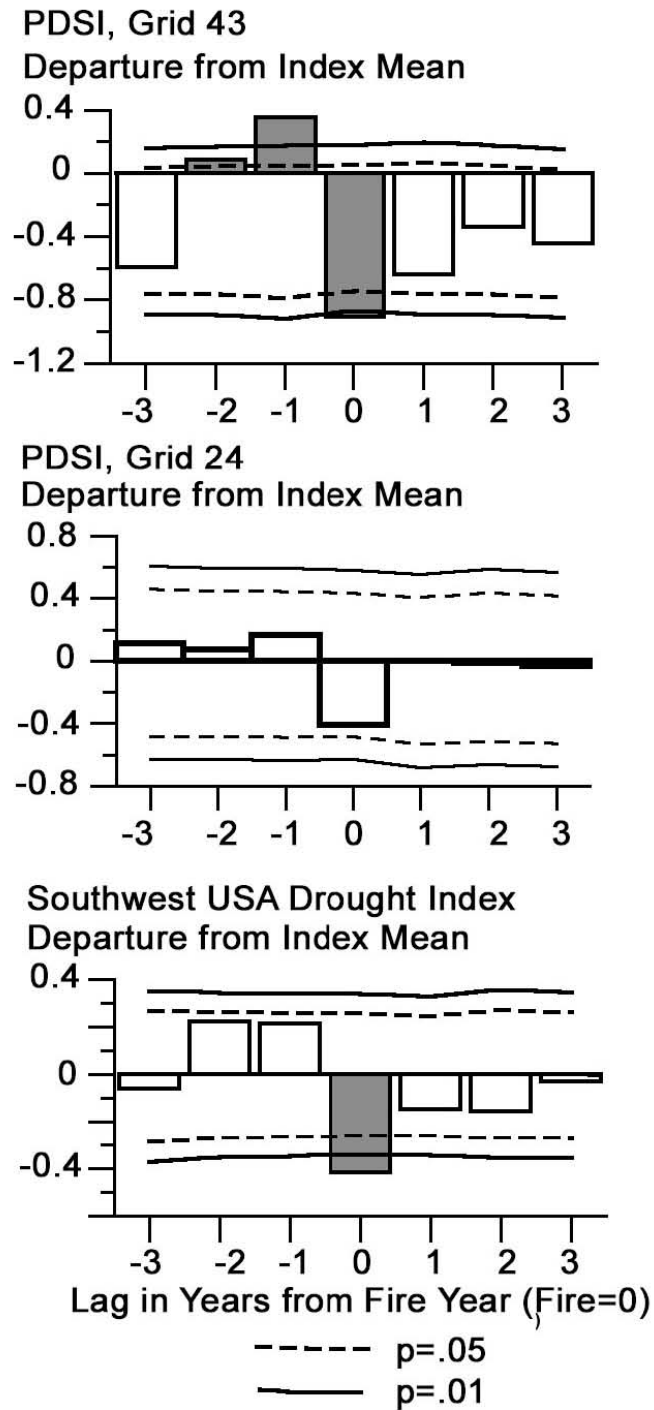


Figure 5. Superposed epoch analysis of fires scarring more than 10% of specimens compared to four proxy climate indices.

4.2.2. Sierraville

One hundred and four fires were identified from 17 specimens at this site. Fires

were recorded between 1610 and 1994. Fires were found to have been frequent during the period of record (Figure 6). Fire scar samples were relatively rare in this site because the 1994 Cottonwood wildfire burned through this site and burned away some of the fire scar record. This wildfire caused little mortality to the overstory Jeffrey pine trees but did kill groups of sapling-sized trees.

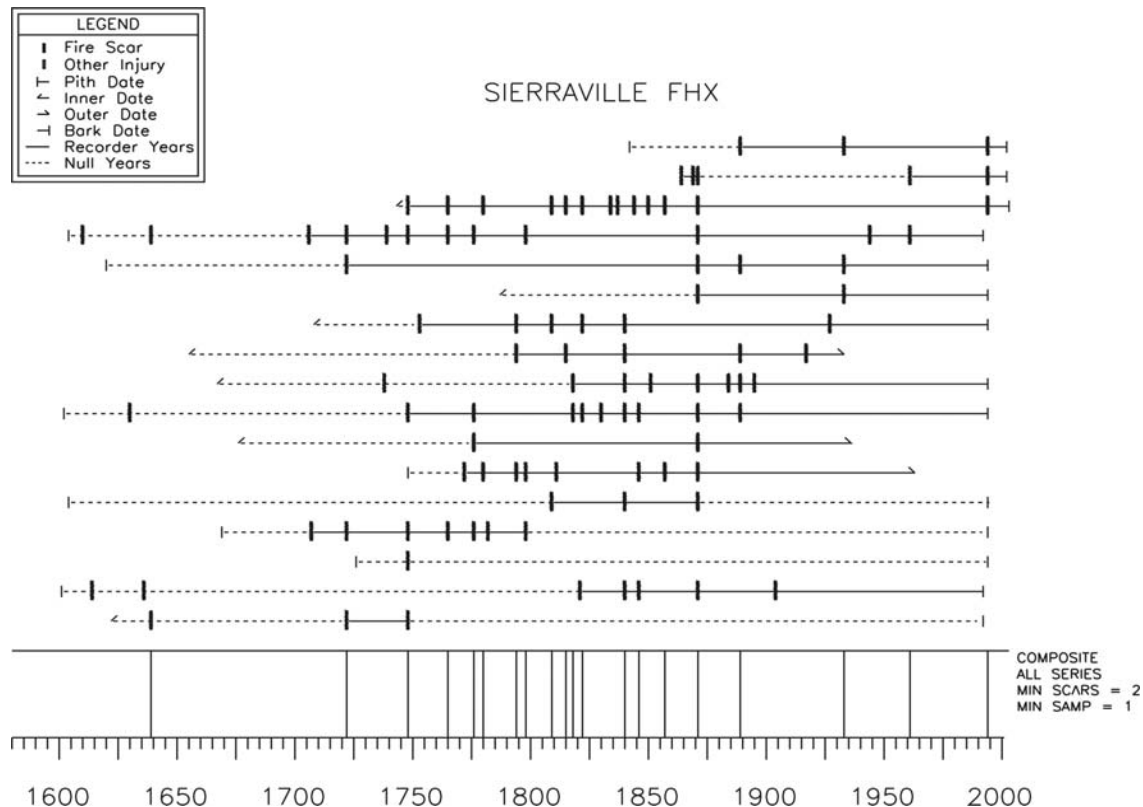


Figure 6. Historical fire activity of Lemmon Canyon, Sierraville Ranger District, California.

Though fire scars were dated back to 1610, the number of fire scarred specimens drops off rapidly before 1750. We selected 1750 as the cutoff date for composites based on visual inspection of Figure 6. Mean and median fire return intervals varied depending on the composite scale selected and number of trees required to be scarred before the fire is recorded in the composite fire summary. Using all samples, the median fire return interval was 5 years (mean 7.5 years), range 1-67 years. Using a filter where a minimum of 10% of possible recording trees were scarred resulted in a median fire return interval of 6 years (mean 10.4 years), range 1-67 years. Median fire return intervals in the forests in Lemmon Canyon are similar to forests dominated by similar species in the eastern Sierra Nevada, California (Stephens 2001) and those in the SSPM (Stephens et al. 2003).

Intra-annual ring position of the scars was determined for 79% of scars. 92.7% of these fire scars were latewood and dormant season fires (Table 8). A dormant season fire in 1871 occurred in multiple samples and a significant pulse of Jeffrey pine regeneration followed this event between 1871-1880.

Table 8. Position of fire scars within annual growth rings from fire scar specimens from Lemmon Canyon, Sierraville Ranger District, California.

Season	Percent of total with season
D	90.2
EE	0
ME	4.9
LE	2.4
LW	2.4

Fires that scarred more than 10% of trees in the study sites occurred during years of low precipitation (PDSI12 $p < .01$; PDSI13 $p < .01$ (Figure 7). Years in which fires scarred <10% of sampled trees or in which no fire was detected showed no association with the precipitation indices.

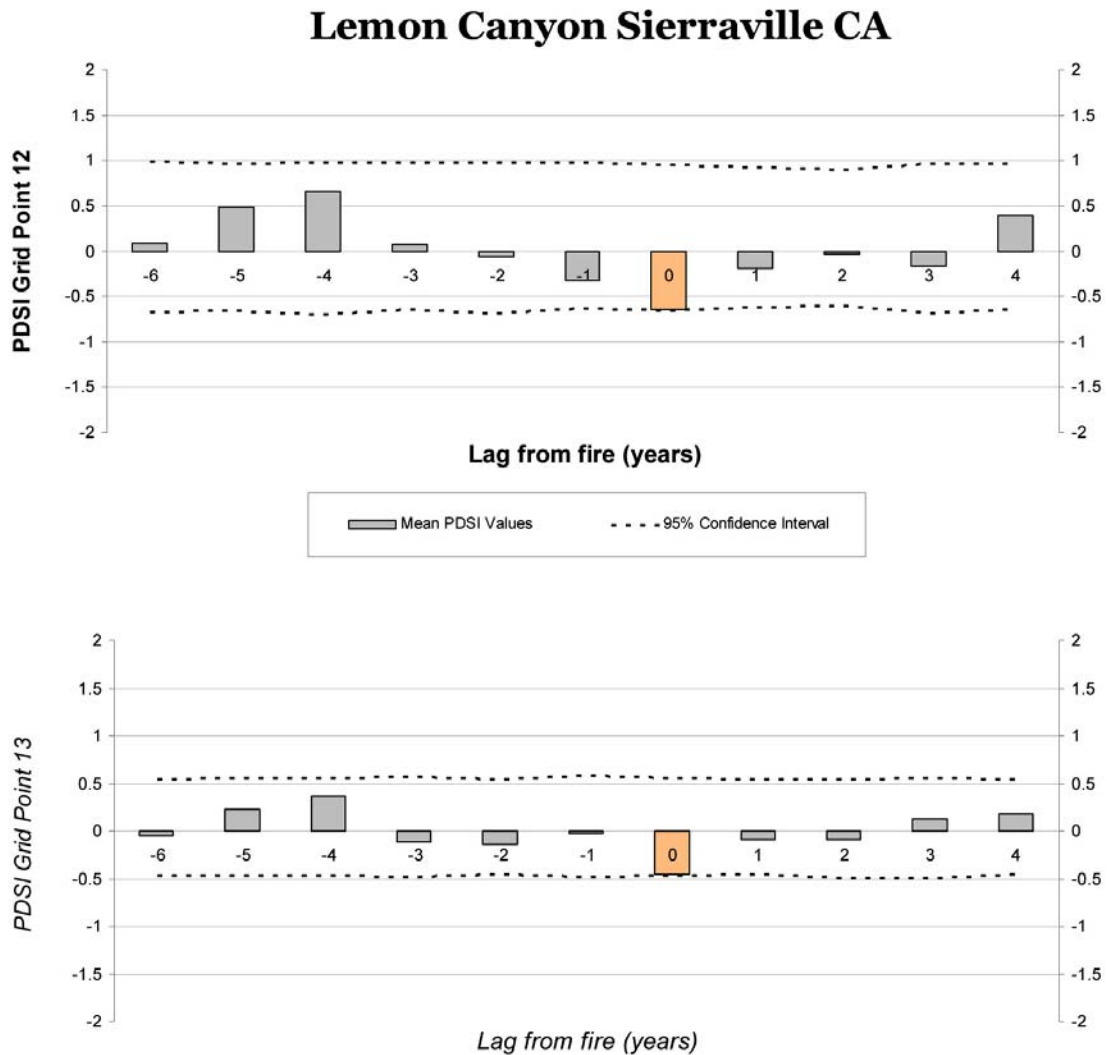


Figure 7. Superposed epoch analysis of fires scarring more than 10% of specimens compared to four proxy climate indices (PDSI 13, eastern Lake Tahoe. PDSI 12, northwest Nevada).

Fires that scared more than 10% of trees in the study sites occurred during years of high San Francisco Bay salinity (Figure 8) as further indication of regionally dry years (Stahle et al. 2001).

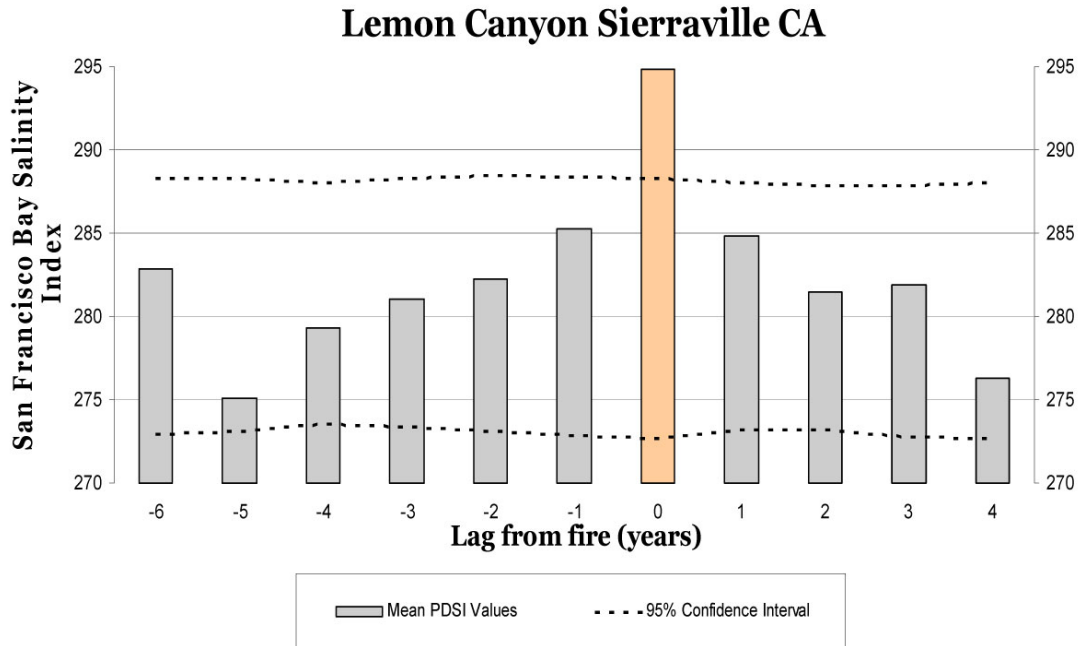


Figure 8. Superposed epoch analysis of fires scarring more than 10% of specimens compared to San Francisco Bay salinity index for Lemmon Canyon, Sierraville Ranger District.

4.2.3. Bridgeport

Two hundred twenty fires were identified from 21 specimens at this site. Fires were recorded between 1570 and 1932. Fires were found to have been frequent during the period of record (Figure 9). Most fire scar samples were taken from live and dead Jeffrey pines.

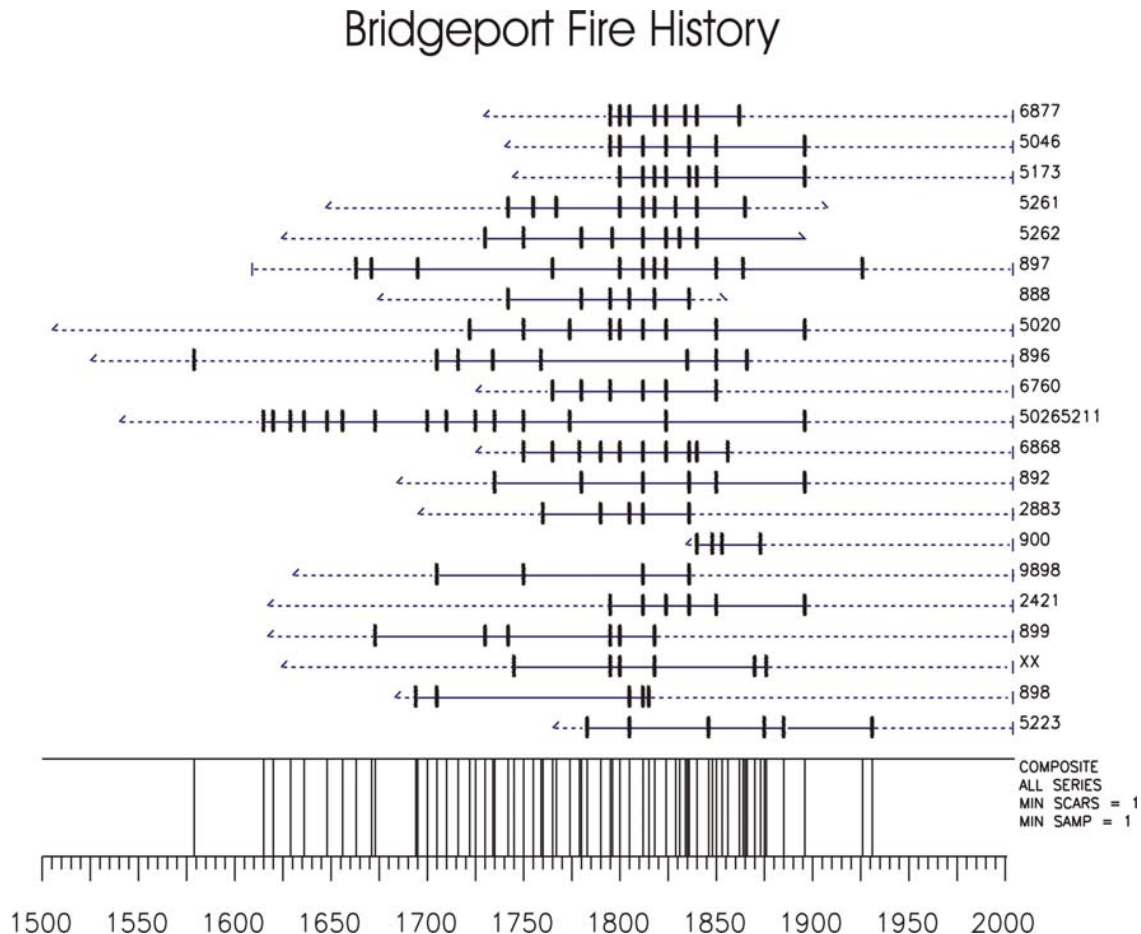


Figure 9. Historical fire activity of Cannon Creek, Bridgeport Ranger District, California.

Though fire scars were dated back to 1570, the number of fire scarred specimens drops off rapidly before 1725. We selected 1725 as the cutoff date for composites based on visual inspection of Figure 6. Mean and median fire return intervals varied depending on the composite scale selected and number of trees required to be scarred before the fire is recorded in the composite fire summary. Using all samples, the median fire return interval was 5 years (mean 5.5 years), range 1-36 years. Using a filter where a minimum of 10% of possible recording trees were scarred resulted in a median fire return interval of 6 years (mean 8.6 years), range 1-36 years. Median fire return intervals in the forests in Lost Cannon are similar to forests dominated by similar species in the eastern Sierra Nevada, California (Stephens 2001) and those in the SSPM (Stephens et al. 2003).

Intra-annual ring position of the scars was determined for 82% of scars. 89.5% of the fires that were recorded within the study site were latewood and dormant season fire scar (Table 9).

Table 9. Position of fire scars within annual growth rings from fire scar specimens from Lemmon Canyon, Sierraville Ranger District, California.

<i>Season</i>	<i>% w/Season</i>
D	89.5
EE	0
ME	7
LE	0
LW	3.5

4.3. Regeneration Structure

4.3.1. Sierra San Pedro Martir

A total of 8.4 km in line transects were surveyed for sapling regeneration patches within the 144 ha systematic grid area. Fifty-four sapling patches were intersected and measured. On average, 7.7 patches (S.E. 1.4) were intersected on each 1200 m transect. Using our definition of a sapling regeneration patch, a small portion of the forest was in patches as indicated by the estimates of patch fraction (3.8%) and patch abundance (8.5 ha⁻¹) (Table 2).

The 18 patches measured in detail (detailed patches) were irregular in shape and 14 of the 18 had a non-convex shape. The area of the smallest detailed patch was 6.6 m² (0.0007 ha) and the largest was 551.3 m² (0.055 ha) (Table 9). The average ratio of the axes (A-major/A-minor) for the detailed patches was 2.15 and for the other 36 patches the average was 2.23.

Table 10. Sapling regeneration patch characteristics of an old-growth Jeffrey pine-mixed conifer forest in the Sierra San Pedro Martir, Mexico. S.E., standard error of the mean.

Patch fraction (%) ¹	3.80 (0.24)
Patch abundance (#/ha) ¹	8.54 (4.60)
Average area (ha) (1 S.E.) [range]	0.010 (0.002) [0.001 – 0.06]
Average perimeter (m) (1 S.E.) [range]	36.9 (3.8) [6.3 – 153]
Average number of trees (1 S.E.) [range]	16.9 (2.7) [3 – 111]
Average number of seedlings (1 S.E.) [range]	9.5 (1.8) [0 – 71]

¹ The numbers in parentheses are the 95% confidence intervals based on a t-distribution.

Assuming sapling patches were shaped as an ellipse overestimated patch area by an average of 34.1% compared to the area calculated from the detailed patches. Assuming the patches were shaped as a rhombus gave the lowest error. The equation for the area of a rhombus underestimated patch area by an average of 1.1%. Although our regression equation showed a significant relationship ($R^2=0.942$, $p < 0.0001$), the intercept was significantly different from zero. Furthermore, the few large patches that were measured in detail strongly influenced the regression relationship and the regression residuals showed a nonrandom pattern. Using the regression coefficient underestimated patch area by an average of 41.5%. Based on these comparisons, the sapling regeneration patches in this forest were most accurately estimated assuming patches were shaped like a rhombus.

The majority of the sapling patches were small (Figure 10); 64.8% were less than the estimate of average patch area. Four patches (7.4%) were more than four times the average patch area. The perimeter of the smallest detailed patch was 6.4 m and the largest was 158.7 m. The average perimeter of the smallest convex cover for the detailed patches was 37.1 m, 0.8% less than the estimated actual average perimeter.

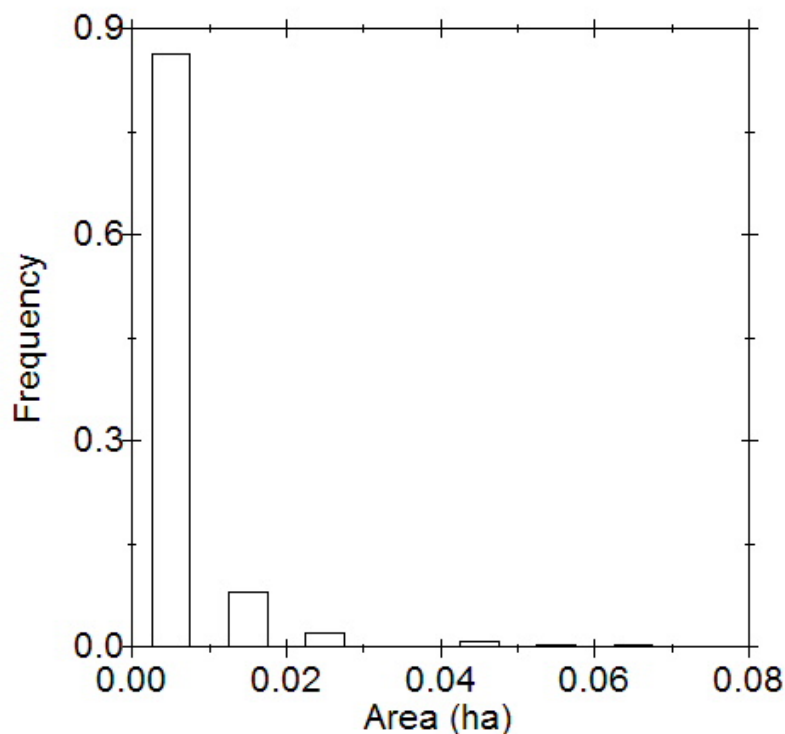


Figure 10. Frequency distribution of sapling patch size (ha) in Jeffrey pine-mixed conifer

The regression coefficient generated by the linear regression model for patch perimeter was similar to the coefficient in the perimeter equation for a rhombus (2.04 and 2, respectively). The regression coefficient generated from the linear regression model using the smallest convex perimeter as the dependent variable was also 2.0. Therefore,

perimeters of the patches were assumed to be shaped like a rhombus. This agrees with the comparisons for the equation for patch area. Using the regression coefficient to estimate patch perimeter overestimated the perimeter by 10% compared to the perimeter estimated from the detailed patches.

Average canopy cover for the 49-plot grid area was 25.3% (S.E. 3.81, range 14 – 49.5%) (Stephens and Gill 2005). Jeffrey pine was the species that dominated canopy cover (average of 19.2%) followed by white fir (average of 5.6%) (Stephens and Gill 2005). Average canopy cover inside sapling regeneration patches was 6.2% (S.E. 1.8, range 2 – 37.1%).

For all forest characteristics compared, average values inside the sapling patches were significantly different than the 49-plot grid (p value <0.01 for all tests). Average DBH was 60% smaller inside the sapling patches compared to the grid plots. Jeffrey pine was the dominant species both inside the sapling regeneration patches and in the 49-plot grid (Table 10). The next most abundant species was white fir, both sugar pine and lodgepole pine were relatively uncommon.

Fifty-six trees inside the sapling regeneration patches were cored and average age was 72.1 years (S.E. 3.7). Average age for Jeffrey pine (n=41) was slightly less than the overall average (average of 70.9 years, S.E. 4.5 years) while white fir was higher (average of 77 years, S.E. 7.7). Cooper (1960) found high densities of 40 year old saplings in ponderosa pine forests in the Southwestern US.

Table 11. Percent species composition by size inside sapling regeneration patches and from a systematic inventory in an old-growth Jeffrey pine-mixed conifer forest in the Sierra San Pedro Martir, Mexico.

Species	Inside patches	Trees	Seedlings	General forest
		General forest	Inside patches	
PIJE	86.8	74.1	78.6	81.2
ABCO	10.6	17.7	11.7	10.8
PILA	1.4	5.9	9.2	7.7
PICO	1.2	2.3	0.6	0.3
<i>N</i>	<i>910</i>	<i>730</i>	<i>513</i>	<i>611</i>

4.3.2. Sierraville and Bridgeport

The diameters at Sierraville follow a normal distribution while the diameter distribution of the Bridgeport site is inverse J shaped (Figures 11 and 12). Most of the trees at Bridgeport are in the small (< 20 cm) diameter classes; 78% of the trees larger than 2.5 cm DBH were between 2.5 and 20 cm DBH. In contrast to the diameter distribution at Sierraville, Bridgeport has a relatively even proportion of trees in the 10 to

50 cm classes; 86% of the trees are in the 10 to 50 cm classes and only 8.5 % are in the smallest class. Not only were a lot more dead trees found at the Sierraville plot, but the dead trees were more evenly distributed over all diameter classes. 20 % of the dead trees at the Sierraville site are larger than 50 cm in diameter, while only 9 % are larger than 50 cm at the Bridgeport site. The 1994 Cottonwood wildfire caused the mortality found in the Sierraville site.

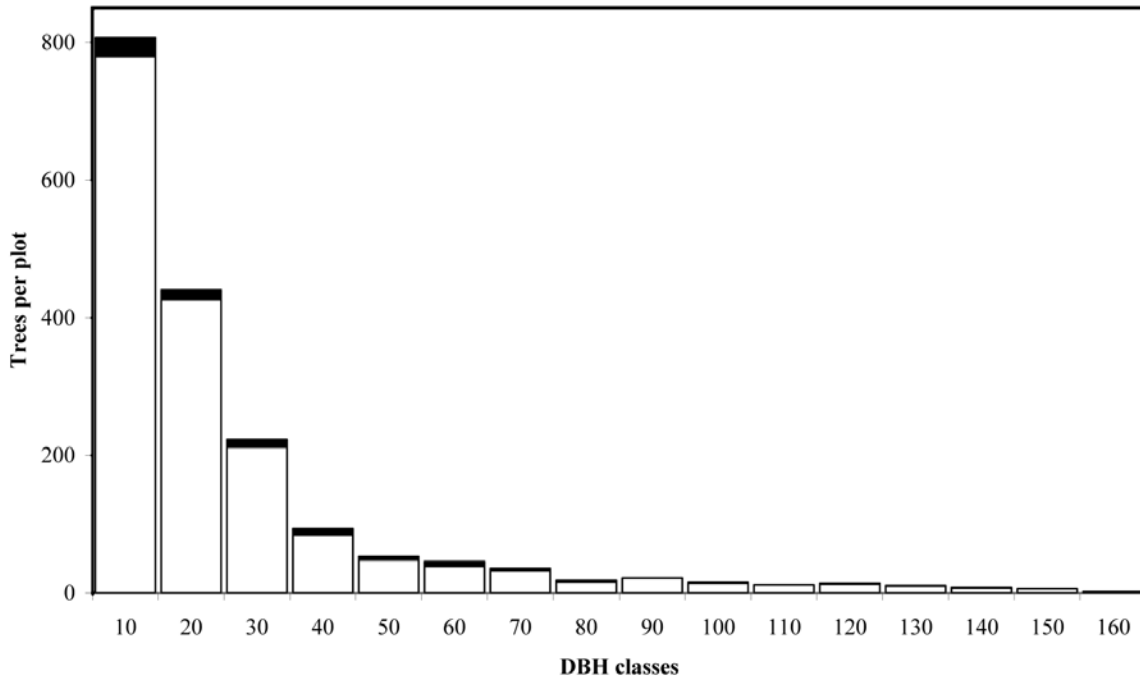


Figure 11. Diameter distributions of living (white) and dead (black) trees at the Bridgeport 4 ha stem map plot. Labeled diameters are the upper endpoints of 10-cm classes.

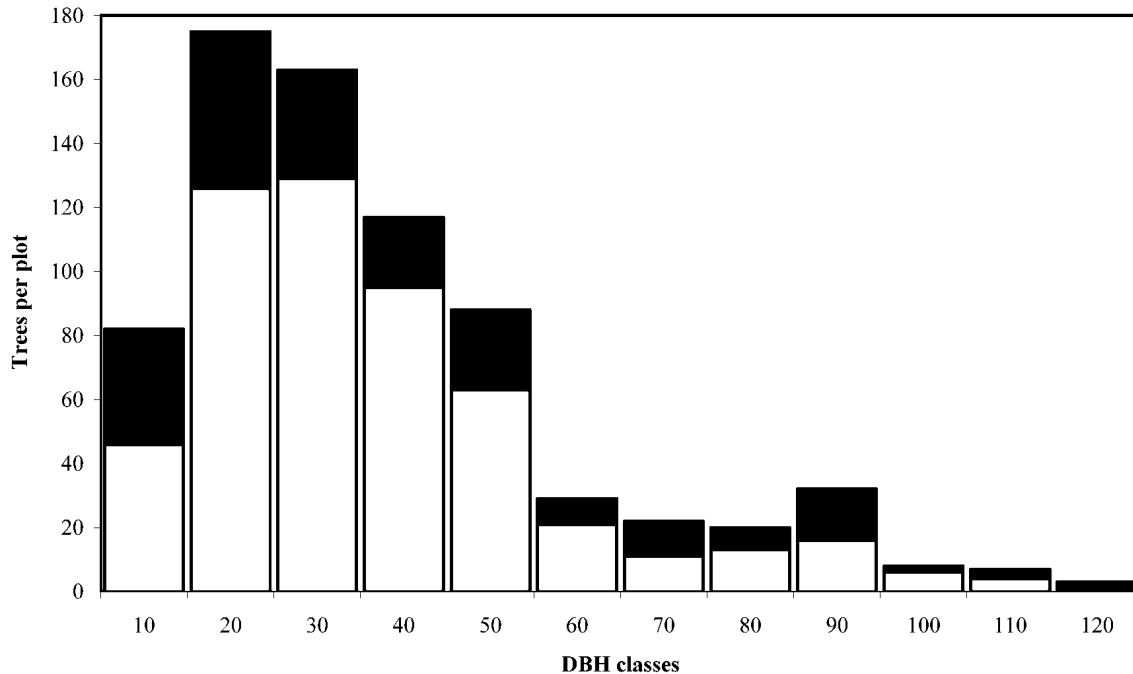


Figure 12. Diameter distributions per plot of living (white) and dead (black) trees at the Sierraville 4 ha stem map plot. Labeled diameters are the upper endpoints of 10-cm classes.

Spatial analysis with the Ripley's-K function revealed a high degree of clumping for distances up to 15 m at both the Sierraville and Bridgeport sites. This clumping was significant at the 95%-level. Understory and small trees are clumped at all scales. Spatial patterns of overstory trees show more variability. The biggest classes (>100 cm) at Bridgeport are randomly distributed at all scales. The largest diameter class also has a random pattern at Sierraville. Pines are more clumped than other species. The distribution of pines at both eastern Sierra Nevada sites for regeneration and understory / overstory is significantly different from random (Tables 11 and 12).

Table 12. Spatial distribution of trees (under- / overstory) on the Bridgeport site, in size classes and for the entire forest. Random (○) or clumped (+) distribution as determined by Ripley's-K analysis. Size class N Distance (t) in meters

Size class	N	Distance (t) in meters									
		1	2	3	4	5	6	7	8	9	10-15
1-9	1,598	+	+	+	+	+	+	+	+	+	+
10-39	756	+	+	+	+	+	+	+	+	+	+
40-99	193	+	+	+	+	+	+	+	+	+	+
100-180	59	○	○	○	○	○	○	○	○	○	○
1-180	2,606	+	+	+	+	+	+	+	+	+	+

Table 13. Spatial distribution of trees (under- / overstory) on the Sierraville site, in size classes and for the entire forest. Random (○) or clumped (+) distribution as determined by Ripley's-K analysis. Size class N Distance (t) in meters

Size class	N	Distance (t) in meters									
		1	2	3	4	5	6	7	8	9	10-15
1-9	453	+	+	+	+	+	+	+	+	+	+
10-39	210	+	+	+	+	+	+	+	+	+	+
40-79	44	+	+	+	+	+	+	+	+	+	+
80-218	33	○	○	○	○	○	+	+	+	+	+
1-218	747	+	+	+	+	+	+	+	+	+	+

At Bridgeport, regeneration trees have no spatial association to trees of any larger size class (for distances below 7m) and therefore, the trees of the smallest size classes are distributed independently from the position of older trees. However, a significant clumping between regeneration and the 10 to 39 cm DBH class at all distances was detected. The Sierraville site reveals a positive association between the regeneration classes and all other DBH classes. Although the regeneration at the Sierraville site is clumped, it has a spatial association at all scales to larger trees (Table 13).

Table 14. Spatial association between regeneration and bigger trees of different dbh classes at Bridgeport. Negative association (-) (repulsion), Positive association (+) (attraction) or no spatial association (○) for distances up to 15 m. Size class N Distance (t) in meters

Size class	N	Distance (t) in meters									
		1	2	3	4	5	6	7	8	9	10-15
Reg vs. 10-39	1,547	+	+	+	+	+	+	+	+	+	+
Reg vs. 40-99	984	○	○	○	○	○	○	○	+	+	+
Reg vs. 100-180	851	○	○	○	○	○	○	+	+	+	+
Reg vs. 2.5-180	2606	+	+	+	+	+	+	+	+	+	+

5. DISCUSSION

5.1. Fire History

5.1.1. Altered Fire Regimes

The SSPM is unique within the California floristic province in that this large, forested area has not been affected by logging and only recently by fire suppression. However, it is obvious from Figure 4 that the fire regime in the later part of the 20th century is not representative of earlier periods, especially before 1800. Indeed, the current fire-free interval is either the longest or one of the longest in the entire record depending upon the composite scale chosen. In the following sections we will explore the possible explanations of why the SSPM fire regime changed around 1800 and why the current period is anomalous.

We hypothesize there are three potential causes of the apparent change in the fire regime that began with the long disruption of fire occurrence at the end of the 18th century. 1) The San Pedro Martir mission was established in 1794 and was briefly occupied through 1806. During this period, livestock grazing was introduced to the SSPM (Stephens et al. 2003). The introduction of livestock grazing, with its impact on the herbaceous fuel layer, has been associated with changes in fire regimes in other areas of western North America (Savage and Swetnam 1990; Touchan et al. 1995). 2) Major declines in native populations (Cook 1971) and accompanying disruptions of native land-use patterns have been generally associated with European settlement and are associated with changes in fire frequency and occurrence (Carpio and Swetnam 1995). 3) Changes in regional climate that have been noted in other parts of the southwestern US and northern Mexico (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Kitzberger et al. 2001).

Grazing. The SSPM Mission was unique among the California mission system in that it relied more on livestock for sustenance than on crops (Meigs 1935). The number of livestock in the SSPM was described as “well up to the average mission herd” and in

1801 consisted of 700 cattle, 500 sheep, 150 goats, 50 swine, and 169 horses, mules, and donkeys (Meigs 1935). In 1800 the herd was reported to have 100 fewer cattle, 100 fewer sheep, 30 fewer horses, and 150 more goats and most were located near meadows.

Though all indications are that herds were small until the mid to late 1800s, the introduction of grazing may have affected fuel continuity due to the low productivity of the area. Reduction of the light grass fuels could effect the size distribution of wildland fires in the SSPM. The number of livestock in the SSPM early in the 19th century was low, and therefore, the change in fire regime at this time was not likely influenced by early grazing. In the mid to late 19th century the number of livestock increased substantially. This increase in livestock density could have substantially reduced the amount of herbaceous fuels in the forest understory and this could have influenced the fire regime. However, the fire regime had already undergone significant changes.

Native Population Decline. The size of the native populations (Paipai and Kiliwa Indians) in the northern and eastern portions of the SSPM before missionary contact was estimated to be 630 people or 0.63 persons per square mile (Meigs 1935). This was the lowest population density for any area surrounding a Baja California mission. According to the Kiliwa in 1926, the forest covered SSPM plateau was never permanently inhabited by Indians because of the winter cold (Meigs 1935). The plateau slopes were visited annually for pinion pine (*Pinus monophylla* Torr. and Frem.) seeds and the forests were used as an area to hunt deer in the summer. There is no historical record of the native peoples using fire in the forests of the SSPM, although they did use it in the scrublands below the mountains to hunt rabbits (Meigs 1935). Native populations dropped quickly after European contact in Baja California and this was the fundamental cause for the deterioration of the missions (Meigs 1935).

Native peoples of other areas of northern Baja California are reported to have commonly used fire to manage for vegetative resources (Bean and Lawton 1993). The Spanish are known to have discouraged the use of fire because of the immediate reduction in available forage for horses and grazing animals. If the people of the SSPM originally used fire, as did other peoples of Baja California, then their decline and cultural disruption is likely to have influenced the fire regime.

Climate Variation. The period of reduced fire occurrence in the SSPM from approximately 1790s to 1830s coincides with a period of reduced fire occurrence at many sites in the southwestern United States, northern Mexico, and southern South America (Touchan et al. 1995; Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Kitzberger et al. 2001). Following the late eighteenth, early nineteenth century transition (LEENT), many sites have experienced less frequent fires with more synchrony between sites (Touchan et al. 1995; Grissino-Mayer and Swetnam 2000). Our two sites from the SSPM appear to follow a similar pattern of fewer fires with a high proportion of sample trees being scarred in each fire after LEENT (Figure 4).

Kitzberger et al. (2001) found the reduction in fire occurrence to have occurred during a decline in the frequency and amplitude of the El Niño-Southern Oscillation (ENSO). That similar changes took place coincidentally in both North and South America suggests that climate is a likely contributor. It appears that climatic variation played an important role in initiation and possible maintenance of the changes in fire frequency in the SSPM. However, the coincident timing of changes in cultural practices, particularly the possible reduction of fire use by native peoples, are likely to have

contributed to fire regime changes.

5.1.2. Fire Seasonality

The intra-ring location of fire scars are quite different between the eastern Sierra Nevada and the SSPM (Tables 7,8,9). This indicates a difference in the seasonality of fires. Fire scars in the more northern Klamath Mountains and Cascade Range of California form mostly at the ring boundary and are interpreted there as late summer and early fall (Taylor and Skinner 1998; Beaty and Taylor 2001). Fire scars in the southern Sierra Nevada form mostly in latewood (approximately 10% earlywood) and are interpreted there as primarily mid-to-late summer (Caprio and Swetnam 1995; Skinner 2002; Stephens and Collins 2004). Fire scars in the SSPM are primarily located in earlywood, indicating fires of late spring to mid summer. The predominance of earlywood scars is similar to that of Arizona, New Mexico, and northern Mexico (Grissino-Mayer and Swetnam 2000). This pattern is considered typical of fire regimes in the dry spring/early summers of the summer-monsoon climate of northern Mexico and the southwestern United States.

5.1.3. Fire Suppression

Past fire frequency in the three sites investigated in this work (SSPM, Sierraville, Bridgeport) are similar. However, the cultural histories of each site are quite different with the SSPM experiencing limited fire suppression beginning in 1970 whereas both California sites have experienced fire exclusion since the early 20th century.

5.2. Snags and Fuel in the SSPM

High variability characterized all snag and fuel attributes measured in the SSPM Jeffrey pine-mixed conifer forest. This high amount of variability is probably the result of the relatively intact frequent, surface-fire regime and because no tree harvesting has occurred in this forest. The high variability in surface fuel loads would produce equally diverse fire behavior and effects, and this would likely help to maintain high spatial heterogeneity if the forest continues to burn under a low intensity fire regime.

5.2.1. Snags

Because of declining populations of some old-growth associated wildlife species such as Californian (*Strix occidentalis occidentalis*), Northern (*Strix occidentalis caurina*), and Mexican (*Strix occidentalis lucida*) Spotted Owls, management guidelines have been developed for the abundance of snags and downed woody material in forests in the western US (Thomas et al. 1990; Verner et al. 1992; Ganey 1999). Many of these guidelines call for the average of characteristics (such as snag density) found across many stands to be created at the stand level, and replicated for all stands across very large spatial scales. The California spotted owl is reported to inhabit the forests of the SSPM.

Current management standards in US Forest Service lands in the southwestern US (Arizona and New Mexico) require 4.9 and 7.4 snags/ha in ponderosa pine and mixed conifer forests, respectively, with a minimum DBH of 46 cm and minimum snag height of 9 m (Ganey, 1999). In the Lake Tahoe Basin of California and Nevada, old-growth forest structure is reported to have a minimum of 5 snags/ha that are > 76 cm DBH (mean snag density 16/ha). The forest series included in this recommendation include Jeffrey pine, mixed conifer, white fir, and red fir (Barbour et al., 2002).

Jeffrey pine-mixed conifer forests in the SSPM have similar snag densities as those reported in Ganey (1999) and are in the lower range of Barbour et al. (2002) recommendation. However, no snags were found on 28% of plots. Average snag density of 5/ha is similar to that found in other pine-dominated forests before harvesting or fire suppression (Stephens 2004) but this density was produced by approximately 50% of the inventoried area in this study.

The majority of snags in the SSPM have large diameters, 85% have a DBH > 30 cm, and 63% have a DBH > 50 cm (Stephens 2004). There are very few small, dead trees in the SSPM (only 7% with DBH < 10 cm). This is in contrast to ponderosa pine and mixed conifer forests in Arizona and California, where current snag populations are dominated by small snags (Ganey 1999; Barbour et al. 2002). Fire suppression has increased tree density and canopy cover in many western US forests and the resulting competition has probably contributed to the high number of small dead trees. This same condition has also led to less potential for replacement of snags with other large trees when the snags collapse (Dolph et al. 1995; Minnich et al. 1995).

5.2.2. Fuel Loads

Average total surface fuel loads are relatively low (15.8 tons/ha) in the Jeffrey pine-mixed conifer forests of the SSPM but there is great variation (range 0.01 – 159.74 tons/ha). Average 1-100 hr fuel loading was 2.2 tons/ha (range 0 – 16.7) while the average 1000 hr load was 13.6 tons/ha (range 0 – 160) (Table 3). Seventy-three percent (35) of sampled plots had surface fuel loads that were below the 49 plot mean. Approximately 25% of plots had moderate fuel loads (18.4 tons/ha), and a few (8% of plots) had relatively high surface fuel loads of 36.8 tons/ha. Thousand-hour fuels were equally patchy.

Average 1-100 hr fuel loads in eastern Sierra Nevada Jeffrey pine forests were 3.13 tons/ha (Stephens 2001) compared to the 2.2 tons/ha in the SSPM. The fine fuel loads from these forests are similar even though they have experienced very different management histories. Fine fuels appear to accumulate slowly in the relatively dry, unproductive, Jeffrey pine-dominated forests and this probably explains why the differences are small. In a more mesic, west-slope mixed conifer forests of the southern Sierra Nevada that has experienced 100 years of fire suppression, average 1-100 hr fuel load was much considerably greater (8.52 tons/ha) (Stephens and Finney 2002). Similar high fuel loads in mixed conifer forests in the southern Cascade Range have been reported (Blonski and Schramel 1981).

5.3. Forest Structure in the SSPM

High variability characterized all tree and seedling attributes measured in the Jeffrey pine-mixed conifer forest in the SSPM. Forest density and basal area in mixed Jeffrey pine forests on the east-side of the Lake Tahoe Basin, Nevada, before Euro-American contact was estimated at 68 trees ha⁻¹ and 26 m² ha⁻¹ (Taylor 2004). The forests sampled in the SSPM had a mean density and basal area of 145.3 trees ha⁻¹ and 19.9 m² ha⁻¹. The difference in tree density can be partially explained by the limitations of sampling old stumps to reconstruct past forest density on the east-side of Lake Tahoe. This study included all trees greater than 2.5 cm DBH whereas Taylor (1998) was able to collect information from only larger stumps that had not decomposed (mostly >15 cm).

The *Pinus: Abies* ratio was 4 to 1 in the forests of the east side of Lake Tahoe (Taylor, 1998) and this is very similar to the forests in the SSPM (4.2 to 1). Modern old-growth Jeffrey pine stands in the Lake Tahoe Basin and those analyzed in the Sierraville and Bridgeport Ranger units have much higher understory (DBH < 40 cm) tree densities than those in the SSPM (averaging 97 trees ha⁻¹) because of fire suppression.

The structure of the Jeffrey pine-mixed conifer forests in the SSPM is diverse. Thirty-three percent of plots included a relatively small number of large trees, 24% of plots had bimodal diameter distributions, and the remaining 43% of plots had inverse-J diameter distributions with many more smaller trees than large trees. Separating these categories into classic seral stage classes is difficult since all plots included relatively large trees. Assuming that size is reflective of age, the plots that had an inverse-J distribution (43% of total) could be classified as multi-aged because of their relatively wide range of tree sizes while plots that contained a relatively small number of large trees could be classified as having a narrower age distribution (33% of total). However, all plots together described an old-growth forest structure since this area has had very few management inputs except livestock grazing and recent, limited fire suppression. Indeed, this old-growth Jeffrey pine-mixed conifer forest includes components of all seral stages in the majority of the sampled plots.

Another forest classification system emphasizes existing forest conditions and processes versus the seral stage of development (Oliver 1981; O'Hara et al. 1994; O'Hara et al. 1996). This system attempts to describe forest structure and to link it to stand development processes that create and maintain it and has the advantage of describing current vegetation structure that is increasingly the basis for describing resource management objectives (O'Hara et al. 1996).

Three of O'Hara et al. (1996) stand structure classes are apparent in the SSPM data 1) old forest single-stratum, 2) young multi-strata, and 3) old forest multi-strata with some modifications. Old forest single-stratum describes a single stratum of medium to large, old trees with one or more cohorts; groups 1 and 2 have these characteristic. This structure can be maintained with frequent, low-moderate intensity fire regimes (O'Hara et al. 1996). Young multi-strata include stands with two or more cohorts with an assortment of trees sizes and canopy strata present but very large trees are absent. This structure is similar to that of group 3 except these SSPM plots do include a few very large trees. This structure is created after periodic disturbances including moderate intensity fires or

harvest events (O'Hara et al. 1996).

Old-forest multi-strata describe stands that are multi-aged with an assortment of trees sizes and canopy strata present including large, old trees. Groups 4 and 5 are multi-sized and include many more small trees versus larger trees (inverse-J distribution). One complication of this stand structure class is the SSPM does not have many multi-strata stands. The relatively intact disturbance regime has developed a forest structure where different canopy strata are separated by space and results in a patchy distribution of trees. A new stand structure class of old-forest, spatially distinct multi-strata could be assigned.

In many areas of California with similar Jeffrey pine-mixed conifer forests, such as Sierraville and Bridgeport, fire suppression and other factors have increased understory tree density. If active management was to include targeted thinning of young trees and prescribed fire, it is probable that succession could be altered so that the pre-contact landscape might be approached in the Tahoe Basin and elsewhere in Alta California.

In order to achieve restoration of more historical stand structures, active management prescriptions would have to incorporate stand-level variation. The forests of the SSPM have a great deal of variation and California forests with similar species, soils, topography, and disturbance regimes would be expected to have similar variation. Restoration of western US Jeffrey pine forests are unlikely to be achieved using uniform stand prescriptions such as all stands must have a specified number of large trees. Methods must be developed to incorporate more variation in stand-level prescriptions. Restoration would more appropriately specify an average conditions at landscape or watershed scales and individual stands would vary about this average similarly to forests with unaltered fire regimes.

5.3.1. Regeneration in the SSPM

The smallest sapling regeneration patch was defined in this work as at least three saplings with a DBH between 2.5 - 15 cm in a 7 m x 7 m area. Only one other patch study (Cooper 1960) has explicitly defined the lower patch size (6.3 m x 6.3 m). Our largest patch size of 0.07 ha is the smallest reported; Cooper (1960) and Bonnicksen and Stone (1981) reported a maximum patch size that is approximately two times larger than this work (Table 14). Other maximum patch size estimates are 4-9 times larger (Table 14). This is the first study to quantify the sapling patch regime in a forest with a relatively intact disturbance regime (fire, insects, disease, drought).

Table 15. Patch size characteristics of Jeffrey and ponderosa pine dominated forests in western North America originally characterized by fire regimes with frequent fires of low-moderate intensity.

Location	Forest type	Patch size (ha)		Source
		Average	Range	
White Mountains, Arizona	Ponderosa pine	0.08	0.06-0.13	Cooper 1960 Cooper 1961
Flagstaff, Arizona	Ponderosa pine	0.07	-	Biondi 1998
Flagstaff, Arizona	Ponderosa pine	0.10	0.02-0.29	White 1985
Flagstaff, Arizona	Ponderosa pine	0.16	0.08-0.64	Moore et al. 1993
Warm Springs Reservation, Oregon	Ponderosa pine	0.26	-	West 1969
Pringle Falls, OR.	Ponderosa pine	-	0.025-0.35	Morrow 1985
Sequoia National Park, CA.	mixed conifer	-	0.03-0.16	Bonnicksen & Stone 1981
SSPM, Mexico	Jeffrey pine-mixed conifer	0.01	0.001-0.07	This work

Age structure data from this study and White (1985) illustrate the variation of successful establishment in Jeffrey pine -mixed conifer and Ponderosa pine forests in northwestern Mexico and the southwestern US, respectively. Part of the variation is likely due to erratic seed production in pre-settlement years that was probably similar to the erratic seed production reported for this century (Larson and Schubert 1970). Some regeneration patches (12%) in the SSPM included moderate sized trees and this was also found in southwestern Ponderosa pine forests. Cooper (1961) found that 2 - 8.2% of the quadrates (6.3 m x 6.3 m) examined in largely intact, old-growth Ponderosa pine forests contained young and mature trees in the same quadrate.

In contrast to the pattern observed by Cooper (1960, 1961) in the White Mountains of Arizona, within group age data in this study and those of White (1985) indicate a wider range of ages within each patch. A possible explanation is that rather than the whole patch of trees dying simultaneously, one or two trees within the patch died and contributed enough additional fuel to a portion of the area to result in a high-intensity fire in that small area. The area thus created would be quite small and only capable of supporting one or two mature trees (White 1985). The concept of Ponderosa pine and Jeffrey pine -mixed conifer forests as a mosaic of groups (Schubert 1974) is upheld by the study of stem spatial distribution, but age data indicate that many groups are not even-aged. That only 25.3% of the SSPM study area was covered by trees (Stephens and Gill 2005) supports the idea that only limited “safe sites” were available for regeneration (White 1985). This is reinforced by the lack of evidence that earlier groups of trees occupied much of the area between current groups in Ponderosa pine forest in the southwestern US (White 1985) and Jeffrey pine -mixed conifer forests in the SSPM.

The majority of regeneration studies done in Ponderosa pine and mixed conifer forests in the US have attempted to quantify regeneration dynamics by sampling older trees (> 100 years) or stumps to remove the affects of US fire exclusion policies. Sampling these older materials does not allow for a direct reconstruction of the size, shape, abundance, and structural characteristics of sapling sized patches. This may be

one reason why the patch characteristics in this work are different (Table 14) than those previously published from forests that also experienced frequent, low-moderate intensity fire regimes.

Before Euro-American settlement in the US, fire enhanced stand patchiness by thinning the small patches of trees that periodically became established. By letting only a few trees per group survive and reach maturity, fire perpetuated patchiness because isolated point source of viable seeds were left across the landscape (Cooper 1960; Biondi 1998). Spatial variation in fuel loads and resultant fire behavior and effects could also contribute to stand patchiness. The SSPM currently has high variability in forest fuel loads and this is probably the result of the relatively intact frequent surface fire regime and because no harvesting has occurred in this forest. The high variability in surface fuel loads would produce equally diverse fire behavior and effects, and this would maintain high spatial heterogeneity if the forest continued to burn under a low-moderate intensity fire regime (Stephens 2004; Stephens and Gill 2005).

Many Jeffrey pine-mixed conifer forests in the eastern Sierra Nevada (including the eastern Lake Tahoe Basin) are largely even-aged because they were almost completely harvested 120 years ago to support the gold and silver mining industries in Nevada and California (Elliott-Fisk et al. 1997). Most of these forests lack the fine-grained pattern of regeneration patches that occur in the SSPM and many have high fire hazards. In addition to the need to manage to reduce fire hazards and promote old trees, small patches of regeneration should also be encouraged. The use of prescribed fire alone or in combination with group selection silviculture could be used to create fine-grained patterns of regeneration. The size of the group selection openings would need to be small in comparison to common group selection practices in California that use openings of 0.1-0.4 ha (Stephens et al. 1999).

In this work, the density of white fir seedlings inside the sapling patches was similar to that recorded from the systematic plot inventory representing the entire forest (Table 10). This indicates that number of shade tolerant white fir seedlings becoming established is almost equal in areas with very different canopy covers (canopy cover of forest = 25.3%; canopy cover of sapling regeneration patches = 6.2%). Forest canopy cover in the SSPM is relatively low and this probably results in high amounts of solar radiation and moisture stress throughout this mountain range which may minimize differences in the location of white fir establishment. Root competition for moisture and nutrients is probably a more significant competition factor in these xeric forests.

Patches continually change in relation to one another, as the trees comprising them grow, reach maturity, die, and are replaced by a new set of young trees. Irregular seed production and seed dispersal by small mammals and birds could help create and maintain the patch regeneration regime in Jeffrey pine-mixed conifer forests in the SSPM; high variation in nutrient availability after fire could also contribute to increased stand patchiness.

5.3.2. Regeneration in the Eastern Sierra Nevada

Interestingly the regeneration in the Sierraville 4 ha stem map is highly aggregated in spite of the high number of regeneration trees. One reason for this pattern is the 1994 Cottonwood fire that burned through this site. This wildfire

killed some patches of saplings and seedlings but also underburned other areas. Mortality to overstory trees was very low. The fire mainly killed the understory layer of white fir that had developed in this remnant old-growth patch of Jeffrey pine-mixed conifer forest. Using a site that had recently experienced a wildfire was not optimal for this project but areas of unharvested Jeffrey pine/mixed conifer forests on granitic parent materials were very rare in the eastern Sierra Nevada. This area did not have any stumps and had an old-growth overstory.

No spatial clustering was found at distances below 6m for bigger trees (> 80 cm) at the Sierraville site and below 15m for trees bigger than 100 cm at the Bridgeport site. One possible explanation is competition for resources is high in areas where the big trees are close to a neighboring tree.

Open and randomly distributed overstories like at the Bridgeport site are consistently associated with areas that once experienced frequent, low-moderate intensity regimes. These fires once thinned regeneration to produce an open and uniform overstory in these forests. Mortality of overstory trees is clumped at both Sierraville and Bridgeport consistent with the thinning role of native insects and disease in areas where fire is suppressed. The dense regeneration at the Sierraville site is also experiencing some level of density-dependent mortality because of competition, this was not observed at Bridgeport.

6. CONCLUSION

In contrast to SSPM forests with a relatively intact fire regime, the forests investigated in the eastern Sierra Nevada have been significantly modified by fire suppression. Most forests in the western US have been modified by both fire suppression and past harvesting and this has increased fuel loads and fuel continuity. Many snags are old in western US forests and are in the latter stages of decay, which increases their susceptibility to fire.

The patchy distribution of snags, live trees, and regeneration observed in the SSPM argues against the application of uniform desired conditions across similar forested landscapes. An improvement in management guidelines would be to manage forest structural attributes over moderate spatial scales (100's of ha) instead of on per ha basis. This would enable managers to meet standards by maintaining high densities or large fuel loads over only a portion of the forested landscape.

Most federal forest restoration and management plans, especially those of the US Forest Service, specify average stand conditions over very large spatial scales (USDA, 2004). This has the advantage of simplicity but is not supported by this data collected from the SSPM. The Jeffrey pine – mixed conifer forests in the SSPM have a great deal of variation in forest structure. It is likely that similar forests in the US also had this high amount of variation because they once experienced comparable disturbance regimes and many had comparable abiotic environments. An improvement in management guidelines would be to allow spatial heterogeneity in desired future conditions.

7. DELIVERABLES AND TECHNOLOGY TRANSFER

Deliverables included: (a) establishment of collaborative relationships with all partners, (b) establishment of research sites, (c) collection of data, (d) reporting of results, and (e) designation of Tahoe National Forest site as demonstration area for technology transfer to professionals and for the education of students and the public. A field trip from the 2005 USFS National Silviculture Workshop discussed the data from the Sierraville site and Carl Skinner provided a summary handout to the participants. The Sierraville site should continue to be an area where staff from the Tahoe National Forest can bring visitors and discuss forest management. The other two sites (SSPM and Bridgeport) are remote and difficult to access. All sites have been tagged with stainless steel tags and therefore will be useful to researchers for at least the next century.

We have a web site at UC Berkeley that summarizes this project as one of those being conducted by the Stephens Lab (<http://cnr.berkeley.edu/stephens-lab/>). All publications from this work are available as PDF files from this site. Stephens and Skinner have given over 15 presentations to professional meetings on this project including annual meetings of the Society of American Foresters, American Geophysical Union, American Association of Geographers, International Association of Landscape Ecology, Northern California branch of the Society of American Foresters, and the Ecological Society of America. They will continue to give presentations on this research. The UC Center for Forestry has been used to direct questions to Stephens regarding this project. Recently an article was written summarizing this work for UC Forest and Farm advisors throughout the state to help them interact with practicing foresters, both federal and private.

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